

Stream restoration: response of benthos to engineered stable riffle/pool habitat

Charles M. Cooper, Sam Testa, III and F. D. Shields, Jr.

Introduction

Habitat degradation is a worldwide phenomenon. In aquatic ecosystems channel incision is a common destructive mode of stream erosion in smaller watersheds which have little or no geologic control to maintain streambed base level. In the United States, resulting channel width increases have been reported as high as 100–1,000%, with associated sediment yields of over 1000 metric tons $\text{km}^{-2} \text{year}^{-1}$. Problems commonly associated with incision include elevated sediment loads, altered hydrologic characteristics resulting from isolation from the floodplain, and loss of normal instream habitat structures such as pools, riffles, woody debris, and undercut banks. Physical characteristics following bank failure and resultant channel widening include shifting bed substrates covered by very shallow and fairly uniform water depths, lack of woody riparian vegetation, and sharper hydrographs during storm events. These changes to the stream ecosystem impact on the biotic community, resulting in altered, and sometimes depauperate populations.

If unassisted, geological time scale is probably needed for recovery from incision-related changes because of the landscape scale impact. Rehabilitation measures are common in degraded stream systems, but restoration of habitats in incised warm-water sand bed streams has received little attention. In this study, we examined the changes in invertebrate community structure elicited by implementation of stabilization structures designed to provide a low-cost approach to restore incised stream channels.

Study sites

We selected 1-km reaches in three northwest Mississippi streams, two of which were located in an agricultural setting and had experienced widespread incision (Goodwin Creek and Bobo Bayou) and one reference site which had not (Toby Tubby Creek). Toby Tubby Creek was 7–9 m wide and about 2 m deep, bordered by a forested wetland, with a total watershed area of about 38 km^2 (12% urban, 15%

cropland, 22% pasture, and 48% forest). Bed material was sand with D_{50} ranging from 0.06 to 0.55 mm. The stream flowed in a sinuous channel with almost total canopy, and large woody debris was common, with occasional beaver dams. Stream bed material was predominately sand, but clay and woody debris were common. Typical riffle substrates (gravel, cobble or rock) were absent, but woody debris and shallow runs interrupted the dominant pool/deep run characteristics of the stream reach. Average water depth was 45 cm. Base flow measurements averaged $0.4 \text{ m}^3 \text{s}^{-1}$.

Goodwin Creek, selected as the test site, has a watershed area of approximately 21 km^2 (13% row crops, 60% pasture and idle lands, and 28% forest). This straightened and historically incised channel was 20–70 m wide and 4–5 m deep. The stream bed was a mixture of sand and gravel (D_{50} , 0.24–8.5 mm), but riffles were unstable and transient. At base flow, the pool habitat (depth >30 cm and velocity <10 cm s^{-1}) composed only 5–20% of the water area. The mean water surface width was approximately 6 m, and the mean depth was 20 cm. Instantaneous discharge measurements averaged $0.06 \text{ m}^3 \text{s}^{-1}$. Stone riprap groins and longitudinal toe protection were placed at locations within and just upstream of the reach during 1989–1991.

Bobo Bayou, our straightened incised reference stream, has a watershed area of about 16 km^2 (13% row crops, 54% idle land and pasture, 33% forest), was 25–29 m wide at the channel top, and 4–5 m deep. Stream bed sediments were sand and gravel similar to those at Goodwin Creek (D_{50} , 0.42–1.5 mm). This creek had considerable canopy cover, but woody debris in the channel was not abundant. Mean depths ranged from 5 to 17 cm at base flow, and discharges at base flow averaged $0.01 \text{ m}^3 \text{s}^{-1}$.

Rehabilitation

Rehabilitation efforts in Goodwin Creek were designed to accelerate the natural evolution of the physical attributes of the stream corridor toward

conditions typical of the non-incised reference (SHIELDS et al. 1992, 1994). Stone riprap was added to extend existing groins across the stream channel to create 18 small weirs at intervals approximately six times the average base flow channel width in the 1-km study reach. Weirs were v-shaped, with vertices facing upstream to focus flow into the center of the channel, with the intention of creating and maintaining scour pools followed by riffle areas through the stream reach. The crests of the weirs were about 2 m wide and 0.6 m higher than the existing streambed except for a 1-m wide central gap left level with the stream bed. One side of each weir was built upon an existing stone groin while the other was inserted into the low-flow channel bank a distance of 3 m. Stones ranged from 0.2 to 450 kg, with 50–85% weighing less than 36 kg. Ninety dormant native black willow (*Salix nigra*) posts, each 1.5 m long by 8–30 cm diameter, were planted along the low-flow bank immediately downstream from each weir. All rehabilitation efforts were completed during the winter of 1992–1993.

Methods

Invertebrates were collected from four 50-m-long regions within the 1-km reaches. Four samples of stream bed sediments, CPOM (coarse particulate organic matter) grab samples, and surface brushings from large woody debris and introduced rock were taken at each creek during each collecting visit unless not available. Bed sediments were sampled using a 5-cm (2-inch) diameter lexan corer to a depth of 10 cm. Three composited cores taken across the stream channel formed each sample. Separate core samples were taken from sand and gravel areas. Each CPOM sample consisted of two composited grabs (total volume of approximately 700 cc) of leaf and/or small twig or other vegetative matter. Introduced rock (riprap) and large woody debris snags were sampled by compositing brushings from two 100-cm² areas and collecting dislodged material and invertebrates with a standard D-frame aquatic net held downstream. No gravel or introduced rock was present at the non-incised reference stream (Toby Tubby Creek). Samples were preserved in 80% ethanol and rose bengal dye was added to aid in sorting. Core samples were first elutriated, then hand picked to remove invertebrates. All other sample types were only hand picked. Invertebrates were usually identified to genus (except Chironomidae: Diptera) and then enumerated. Chironomidae were not identified to genus, but were treated as a single taxon due to the large number of individuals and time and preparation requirements for determination. Thus, values for percent contribution of the dominant taxon

(PCDT) do not include counts of Chironomidae. Data from the four sampling reaches within each creek were composited by sample type and date for each creek to reduce the effects of intra-sample type variation (HARRIS et al. 1995). Subsequent observations are reported from yearly averages computed from both spring and fall sample information unless otherwise indicated to remove seasonal bias. Voucher specimens of each invertebrate taxon are retained in the laboratory reference collection.

Physical habitat characteristics were measured during benthos collection semi-annually (spring and autumn) for 2 years before (1991–1992) and during the 3 years following construction (1993–1995) at 1-km reaches in each stream. The non-incised reference stream (Toby Tubby Creek) was not sampled during spring of 1991. Physical data collection consisted of 75–140 measurements taken along 15–24 transects at each site. Measurements included depth, velocity at 0.6 times the water column depth, bed type, notes on presence and number of beaver dams or man-made structures, and area of large woody debris formations. From these data, summary statistics for pre- and post-restoration were calculated. Scour holes below each weir were measured during summer base flow using a tape and wading rod. The thalweg profile was surveyed 3 months after restoration construction activities, and compared to a profile taken during 1985.

Results

Physical

Scour holes formed rapidly downstream of each weir following construction; the average dimensions were 11 m wide by 14 m long by 130 cm deep. Gravel deposits formed riffle-like features upstream of many weirs. Thalweg profiles showed a stair-step formation along the 18 weirs and associated scour holes similar to riffle-pool progressions in well-developed natural streams. Prior to the construction only four pool areas at irregular intervals were recorded, and observed fill and scour sequences dominated the habitat conditions as sand migrated downstream or was flushed by large events with excessive energy. Post-construction measurements showed local increases in water width of over 100% and local increases in depth of 0–1,000%.

In Goodwin Creek restoration activities produced changes in mean width, depth, and velocity of +56%, +148%, and –67%, respec-

tively. Pool areas (>30 cm depth) increased from 20% of the water area before construction to 53% only 3 months after the restoration activities had begun. After 7 months, beaver activity at seven of the weirs increased the pool area to 75%, the water width was nearly twice the pre-construction values, and the mean water depth approached that of the non-incised reference stream, Toby Tubby Creek. The mean velocity, meanwhile, decreased sharply. High mortality of willow post plantings (~80%) was observed due to competition by Kudzu (*Pueraria lobata*) and other herbaceous species, impermeable or droughty soils, and beaver (*Castor canadensis*) activity. In spite of beaver activity, the large woody debris density in Goodwin Creek remained about an order of magnitude less than the incised reference (Bobo Bayou) and the non-incised reference stream (Toby Tubby).

Changes in the stream bed composition indicate substrate dynamics in incising channels. Goodwin Creek had a 10% decrease in the measured occurrence of sand, with an attendant increase in rock and gravel bed types and a mean particle size diameter (D_{50}) increase from 0.55 to 0.75 mm. The incised comparison stream, Bobo Bayou, incurred larger changes in bed composition as sand substrate decreased more than 35% and large increases of gravel and debris were observed from ongoing channel incision and bank failure. The mean particle size (D_{50}) at Bobo Bayou increased from 0.52 to 2.0 mm. Toby Tubby Creek showed little change during the study, with a small decrease in debris density exposing more clay substrate, and D_{50} (0.4 mm) remained relatively unchanged. A more comprehensive discussion of the physical habitat changes resulting from the rehabilitation efforts is given by SHIELDS et al. (1995).

Invertebrates

During the 5-year study 67,029 invertebrates were collected. The number of taxa (at the genus level) exhibited an increasing trend at all creeks through the first 3 years (1991–1993) of the study (possibly due to long-term recovery following extremely high flows in early 1991). During 1994 (the second year following reha-

bilitation at Goodwin), the number of taxa for all creeks was similar, but during 1995, a distinct and similar decline occurred in both the incised reference stream and the non-incised reference, while taxa at the rehabilitated stream increased. Pre- and post-rehabilitation averages show that the number of taxa increased by eight at both the rehabilitated and non-incised reference stream (~70%), but only by four (32%) at the incised reference (Table 1).

Following rehabilitation, the average number of individuals at Goodwin Creek decreased by 18% from the pre-modification value. This change resulted from a 28% decrease in the average number of Chironomidae present, while there was a 118% increase of the (smaller) non-chironomid component of invertebrates. Numbers of total individuals at the incised reference stream (Bobo Bayou) increased by 166%, and numbers at the non-incised reference (Toby Tubby) increased by 60%. Pre-modification values for the ratio of Chironomidae individuals to other individuals were: Goodwin Creek (15.3:1), Toby Tubby (5.6:1), and Bobo Bayou (6.2:1). Post-rehabilitation values were Goodwin Creek (4.6:1), Toby Tubby (3:1), and Bobo Bayou (11.8:1).

The non-chironomid portion of the fauna at Goodwin Creek before rehabilitation was dominated by three families: Hydropsychidae (Trichoptera – 36%), Simuliidae (Diptera – 28%), and Baetidae (Ephemeroptera – 20%). Other taxa present but contributing less than 10% each included Siphonuridae (8%) and Caenidae (4%) (Ephemeroptera), Annelida (3%), and Physidae snails (1%). Following rehabilitation, Simuliidae made up 50% of all individuals collected, with the next most abundant group being the Annelida (18%). Baetid mayflies decreased to 7%, and Hydropsychid caddisflies decreased to only 6%. Copepoda represented 6% of the fauna, Ceratopogonidae (Diptera) 5%, and Lymnaeid snails 3%. Caenid mayflies contributed only 1%, as did the Hydrophilidae (Coleoptera). Asselid crustacea, physid snails, coenagrionid odonates, and gammarid crustacea each contributed less than 1% to the fauna.

The number of Ephemeroptera, Plecoptera,

Table 1. Average pre- and post-rehabilitation values, and amount and percent change for selected invertebrate sample data. Goodwin Creek (rehabilitated stream), Bobo Bayou (incised reference), Toby Tubby Creek (non-incised reference). (Apparent incongruity of some "Change" column values is due to numerical rounding of other displayed values).

		Before	After	Change	% Change
Number of taxa	Goodwin Creek	13	21	8	65%
	Bobo Bayou	13	18	4	32%
	Toby Tubby Creek	11	19	8	78%
Number of individuals	Goodwin Creek	3367	2763	-604	-18%
	Bobo Bayou	1212	3224	2012	166%
	Toby Tubby Creek	1015	1624	609	60%
Number of EPT	Goodwin Creek	145	73	-73	-50%
	Bobo Bayou	126	160	35	28%
	Toby Tubby Creek	144	225	81	56%
Number of Chironomidae	Goodwin Creek	3142	2271	-870	-28%
	Bobo Bayou	1044	2972	1928	185%
	Toby Tubby Creek	819	1221	402	49%
Number of non-Chironomidae	Goodwin Creek	226	491	266	118%
	Bobo Bayou	168	252	84	50%
	Toby Tubby Creek	147	403	256	174%
Percent contribution dominant taxon	Goodwin Creek	63	44	-19	-30%
	Bobo Bayou	47	45	-3	-6%
	Toby Tubby Creek	49	37	-11	-23%

and Trichoptera (EPT) decreased 50% at Goodwin Creek following rehabilitation, but increased at both Toby Tubby and Bobo Bayou (56% and 28%, respectively). EPT richness (number of taxa in the EPT orders) in Goodwin Creek decreased from an average of seven taxa before rehabilitation to 6.3 afterwards. EPT richness increased at the non-incised reference (from 5.5 to 7.6, average) and incised reference (from 5.5 to 6.3, average) streams. The percent contribution of the dominant taxon (PCDT) decreased by 30% at Goodwin Creek following rehabilitation. PCDT of the reference stream, Toby Tubby, decreased 23%, and PCDT at the incised reference, Bobo Bayou, decreased 6%.

Collector-filterer functional group individuals increased dramatically during the year following rehabilitation at Goodwin, from pre-modification yearly totals of 283 and 283, to

1,423 individuals during the calendar year, 1993. The number of collector-filterer individuals for the next year was only 362, and for the final year of the study was only 13. A similar pattern was observed for the non-incised reference stream, with the total number of collector-filterer individuals expanding from 62 and 427 during the first 2 years of study, to 1,540 individuals during 1993, then decreasing to only 216 and 119 for the final 2 years of the study. The incised reference stream showed no increase during 1993 but rather a decrease in the number of collector-filterers, with observed numbers of 36, 326, 179, 277 and 6 individuals during the consecutive years of the study.

The shredder functional group exhibited a similar pattern at all three creeks, with extremely few individuals collected during the first 2 years of the study, a peak amount captured during 1993, and moderate numbers col-

lected during the final 2 years of the study. Peak numbers during 1993 were highest at the rehabilitated stream, Goodwin Creek, where 268 shredders were collected, while only 115 and 91 were collected at the non-incised and incised reference stream, respectively. The percent shredder individuals of the total individuals collected was lowest at the two incised streams before rehabilitation efforts, and highest at the non-incised reference site. Following rehabilitation, Goodwin Creek increased to a ratio near that of the non-incised reference in the first year, then exceeded the non-incised reference during the final 2 years.

Observed changes in the proportions of functional feeding groups collected from Goodwin Creek before and after rehabilitation are summarized in Fig. 1. Filtering collector, scraper, parasite and piercer group contributions were relatively unchanged. The gathering collector contribution decreased by 70%, while the predator contribution increased nearly 5-fold, and the shredder contribution increased by a factor of 6.

Discussion

The physical response to rehabilitation efforts was generally as expected. Such rapid response patterns of erosion and deposition were typical of those observed by other authors for weirs in

steeper streams, larger rivers, and in physical models. Beaver activity compounded the stream response to the weirs, creating a greater pool habitat at the expense of the riffle area. Though unplanned, this occurrence may represent a return to more natural conditions that existed prior to European settlement in the area. Beaver activity did not affect drainage or cause flooding of adjacent fields due to the water-carrying capacity of the incised creek. As noted above, beaver impoundments were common at the non-incised reference stream.

Biological interactions, especially competition, may dominate community formation and dynamics in constant environments. Physical disturbance, conversely, prevents the continuing domination by a small group of specialized competitors and allows rapid colonizers to co-exist (YODZIS 1986). Stream systems are subject to multiple disturbances that fluctuate widely in intensity and time of occurrence, including seasonal and storm-related hydraulic events and allochthonous inputs of materials from the watershed and upstream channel. Patch dynamics (PATRICK 1975) exemplifies the rapid colonization/reproduction that characterizes stream organisms evolved to inhabit these habitats. In Goodwin Creek, we observed continuing changes in the invertebrate community despite the creation of a more stable riffle-pool

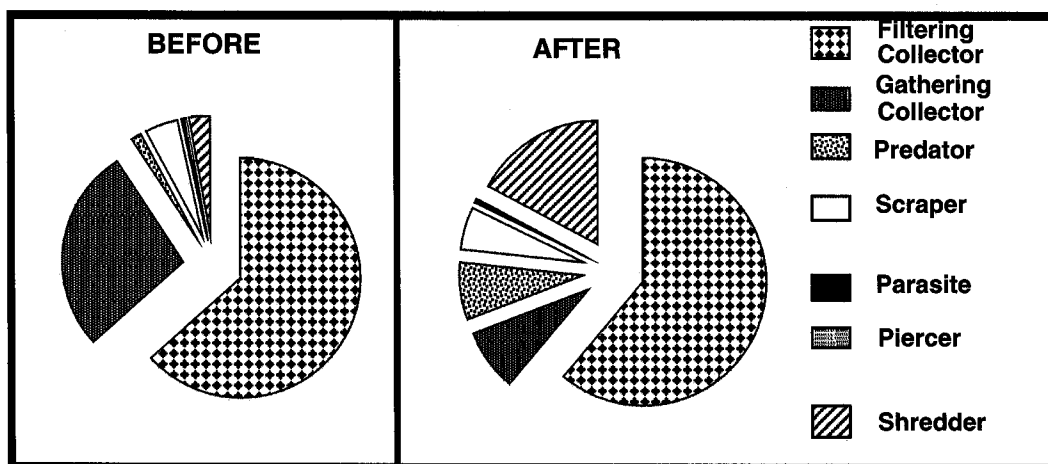


Fig. 1. Percent functional feeding groups before and after rehabilitation in Goodwin Creek, Mississippi.

sequence. We specifically attributed the population shifts to (1) environmental fluctuations, (2) creation of the new riffle-pool sequences with greatly enlarged pools, (3) increased predation from fish, and (4) the rapid colonization ability of aquatic invertebrates.

The first half of our study appears to measure a response to a large-scale event, specifically catastrophic high flow and the resulting large-scale bed substrate movement in 1991. PAYNE & MILLER (1991) found that floods and low flows have potentially major significance in determining the structure and abundance of invertebrate communities in streams with erosive sediments. The similarity in species richness observed during the first 4 years of the present study indicates that a recovery was occurring during the first 3 years and that the communities had recovered by the fourth year. The deviation of the rehabilitated stream from the two reference streams (which decreased in an almost identical manner) during the final year of the study could be attributed to an ability of the rehabilitated stream to withstand (and even improve during) some regional effect which decreased species richness at the reference streams.

In addition to recovery from catastrophic flows, rehabilitation construction increased pool habitat in Goodwin Creek from 20% to 70% of the water surface area. The percent of sand decreased while the stable substrate for invertebrates increased. With this dramatic habitat change, the fish community expanded rapidly. The fish biomass before rehabilitation was 6.8 kg/100 m; after rehabilitation, it was 10.0 kg/100 m. The mean numbers of fish increased from 3,304 fish/100 m to 4,096 fish/100 m. Invertebrates attached to stable introduced rock and natural stream gravel provided the major diet component for key fishes. Gut content analysis on three common fish species found larger following rehabilitation (longear sunfish, *Lepomis megalotis*; bluegill, *L. macrochirus*; and yellow bullhead catfish, *Ameiurus natalis*) showed that their entire diet was composed of substrate oriented invertebrates, except for occasional incidental terrestrial invertebrates. Chironomidae composed over 70% of the gut content in all three species. This explained the

decrease in Chironomidae instead of an expected increase. When pools create vulnerability because prey are conspicuous or lack refuge, predation is most effective (POWER 1992). This basic habitat change also explained some of the observed decline in EPT abundance.

Comparisons of pre- and post-rehabilitation information showed other notable differences between our rehabilitated stream and the two comparison streams. Overall abundance of invertebrate individuals decreased at the rehabilitated stream, while abundance increased at the reference streams. Invertebrate communities in the study streams were dominated by midges (Diptera: Chironomidae). Identification of subsampled representatives of the Chironomidae collected at the incised streams showed that pollution-tolerant species of the *Polypedilum illinoense* and *Dicrotendipes nervosus* groups were most abundant. After rehabilitation, the test stream decreased in chironomid abundance and had an increase in non-chironomid individuals. The reference stream increased moderately in chironomid abundance and greatly increased in the numbers of non-Chironomidae, while the incised reference stream exhibited a very large increase in Chironomidae numbers and only a moderate increase in other invertebrates (Table 1). Although the test stream had a very high ratio of Chironomidae to other individuals before treatment, this ratio was similar to that of the reference stream following rehabilitation.

The % contribution of the dominant taxon (PCDT), an accepted measure of a healthy community, improved at the rehabilitated stream. A high or increased PCDT in a community implies that the community is unbalanced or stressed (PLAFKIN et al. 1989); therefore, a large decrease in the PCDT, as seen at our rehabilitated stream, implies improvement. PCDT at Goodwin Creek decreased by 30% following stream modifications. The non-incised reference stream exhibited a 23% decrease, while the incised reference stream PCDT decreased only 6%.

EPT abundance and richness were not meaningful indicators of success for our study where the creation of a pool habitat was sought. Our

rehabilitated stream exhibited a 50% decrease in EPT individuals following modifications; both the reference streams had increases. The observed decreases in the number of EPT individuals and the number of EPT taxa at Goodwin Creek is most likely explained by changes in the physical habitat (large increases in pool habitat and associated inundation of gravel riffles compounded by beaver activity) and by fish predation which selected against some members of these groups.

The number of collector-filterer group individuals exhibited similar patterns at both the rehabilitated stream and the non-incised reference stream, with the most notable similarity occurring in 1993 when both showed large increases in numbers. Collector-filterers have been shown to be primary colonizers of reclaimed habitat (GORE 1982) and sensitive to sedimentation (LAMBERTI & BERG 1995), and sharp increases in their numbers could be indicative of restored habitat in our stream. Their numbers declined sharply during the second and third year after rehabilitation at Goodwin Creek. This change probably resulted from deeper and slower water characteristics after rehabilitation which decreased the amount of available suspended food particles.

Members of the shredder functional group are sensitive to local and upstream riparian zone effects. Observed increases in the number of shredder functional group individuals during the first 2 years of this project appear attributable to recovery. Following rehabilitation (1993–1995) a similar pattern was observed (though at different scales) at the reference streams. Shredder composition at Goodwin Creek, which had been lower than at the two other creeks, increased greatly following rehabilitation, then exhibited the largest percent contribution of shredder individuals to total individuals of all study streams during 1994 and 1995. We observed that the created riffle-pool sequences allowed better trapping of allochthonous material which favored shredders.

Several indications of stream improvement were observed following rehabilitation of Goodwin Creek: increased taxa richness, much

lower Chironomidae-to-other individuals ratio, a substantially decreased contribution of the dominant taxon, similar changes in the filtering collector communities of the rehabilitated and the non-incised reference stream, and a distinct improvement in the shredder functional group in the rehabilitated stream. The EPT measures of a healthy stream community declined, probably due to physical changes which did not favor these invertebrates, but which promoted a pool habitat inclined toward other invertebrates and certain fish species, especially Centrarchidae (SHIELDS et al. 1995), creating competitive interactions and predation (HARRIS et al. 1995).

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Authors' address:

CHARLES M. COOPER, SAM TESTA, III, F. D. SHIELDS, Jr., U.S. Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, P.O. Box 1157, Oxford, MS 38655, USA.